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Overview of Compact Tori and Spherical Tokamak Researches with TS-3 and TS-4 machines at University of Tokyo

(Comparative studies on the Relaxation of Merging Produced CT/ST plasmas in TS-4)

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Contents

1. Introduction

•In the field of fusion energy researches, plasmas with both of the simpler configuration and the much higher ß (ß=plasma thermal pressure / magnetic pressure) than those of conventional tokamaks allow us to envision the economical viability of fusion energy.

Candidates are compact tori and spherical tokamaks (CT/ST's) that include:

We are trying to understand the systematic properties of various configuration in the q-edge(Itfc/It)-beta domain.

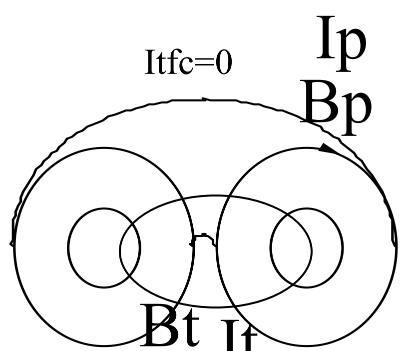
•The field reversed configuration (FRC)

•The compact reversed field configuration(CRFP)

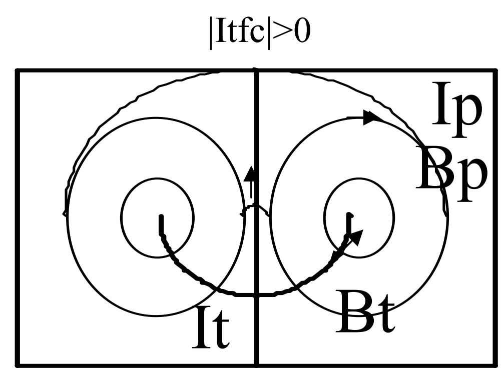
•The spheromak

•The compact VLQ/ULQ,

•The spherical tokamak(ST)



spheromak (Bt>0)
FRC (Bt=0)



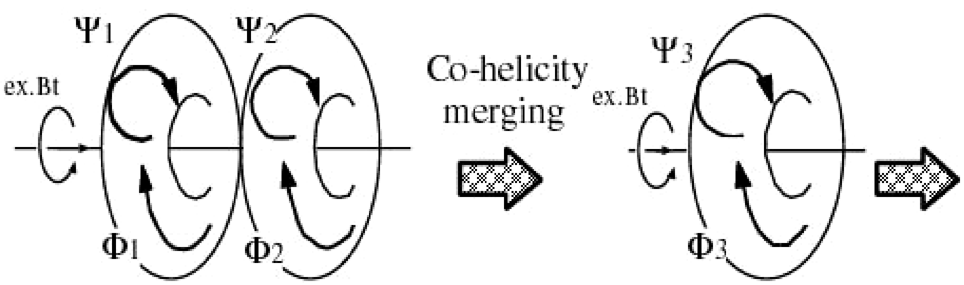
tokamak, ST (Itfc>0)
RFP, compact RFP (Itfc<0)

The merging production of CT/ST plasmas is applied. The magnetic reconnection proceeds much faster than the decay speeds. The merged configuration shows its nature.

total

Poloidal flux: $\Psi_3 = \max(\Psi_1, \Psi_2)$

Toroidal flux: $\Phi_3 = \Phi_1 + \Phi_2$



The merged configuration shows its characteristic nature, which is used to evaluate the configurations.

Original toroidal fluxes:

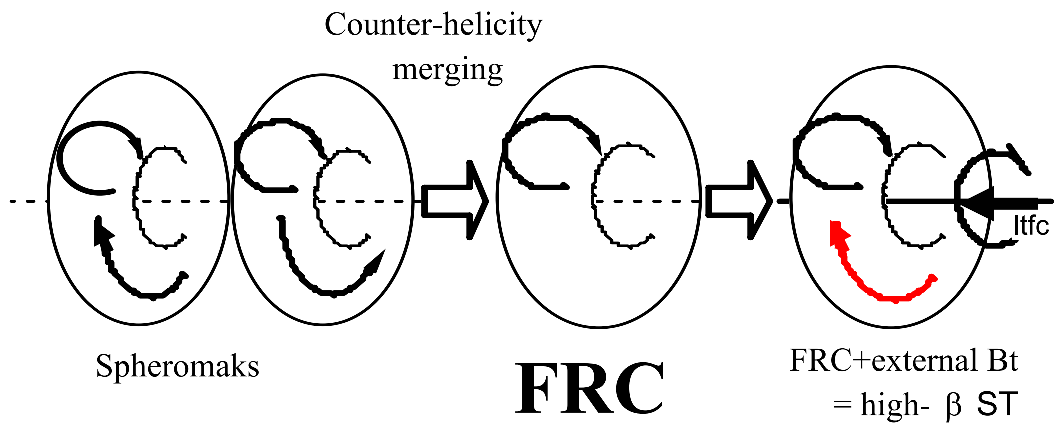
In the same direction: ***co-hlicity merging production***

In the opposite directions: ***counter-helicity merging production***

The merging method is applied to produce high beta FRC and CT/ST.

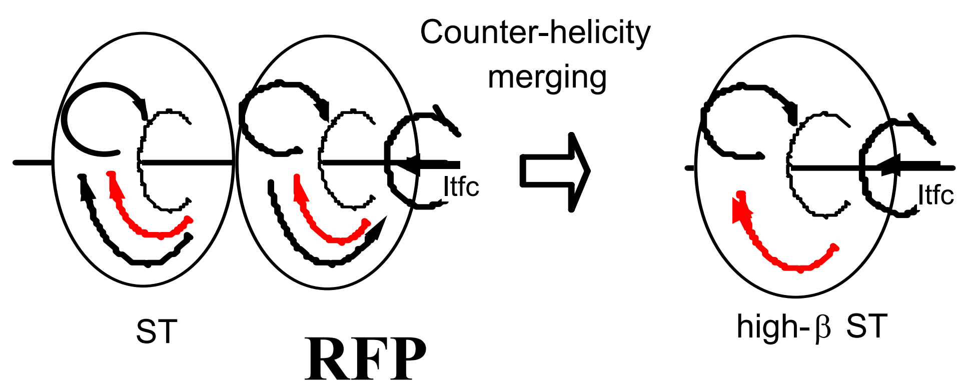
A. Post-injection of B_t

Ramped application of external toroidal field to the FRC



B. Pre-injection of B_t

ST+**RFP** merging in an external toroidal field



2. Objectives

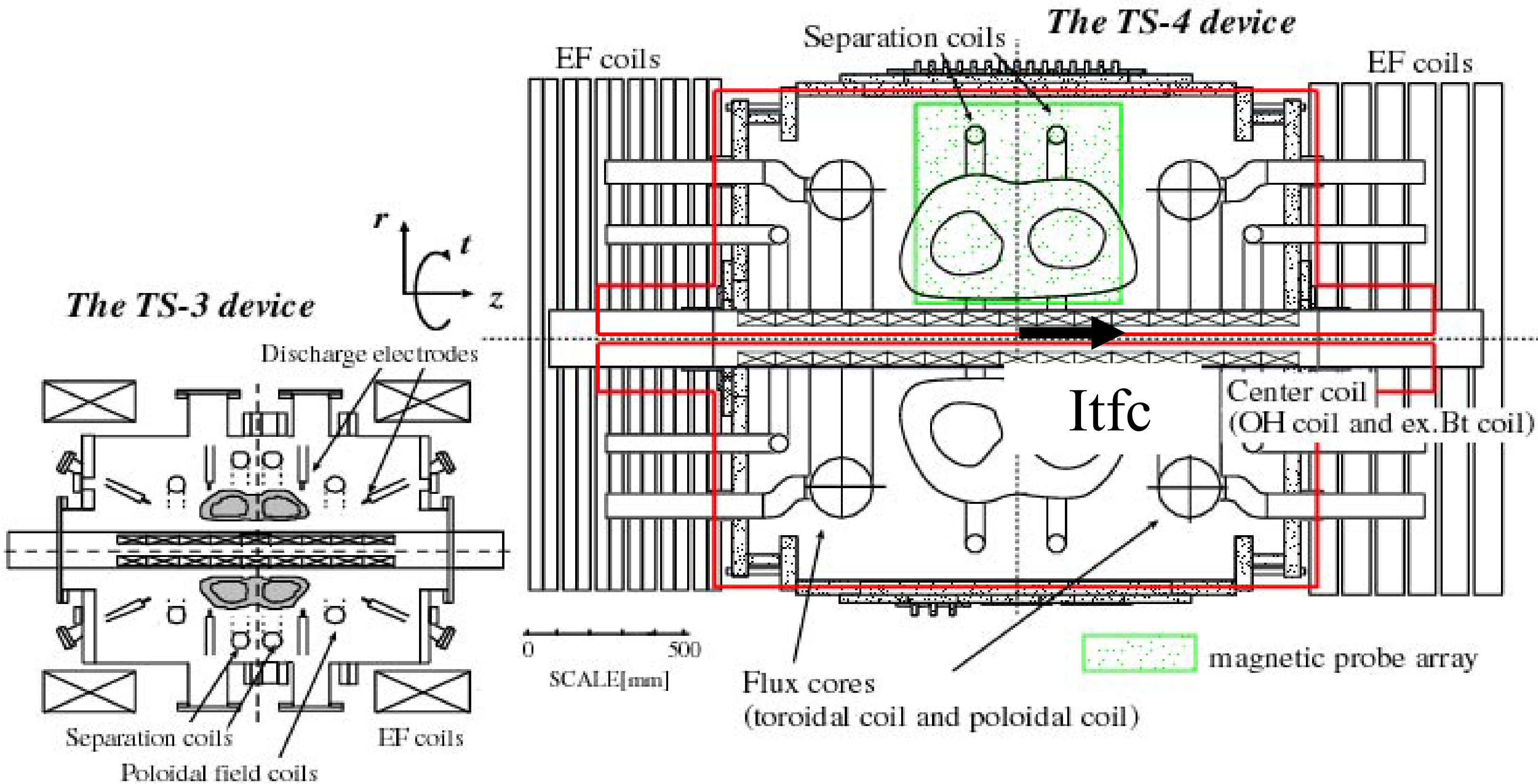
- To develop a novel plasma production method without using the center OH coils that is competent in generating whole types of CT/ST plasmas with an varied q values in an external toroidal field of an arbitrary value ranging from a negative value(RFP) to a large positive value(ST with a large q-edge).

- To make studies on compact RFP plasmas to compare with conventional RFP, and also to investigate its applicability to the ST-RFP counter helicity merging to produce high beta ST's in an expternal toroidal field.

- To carry out the co-helicity merging production of CT/ST's in external toroidal fields to investigate the difference in the nature of MHD relaxation in different kinds of CT/ST configurations to evaluate their MHD performances .

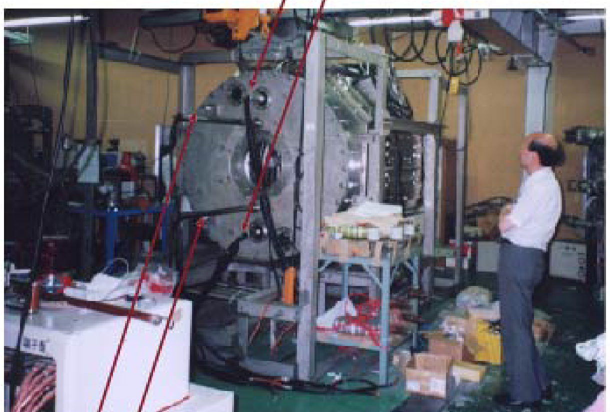
- To investigate the counter-helicity merging for the production of high beta CT/ST plasmas with a varied q-edge value in an external toroidal field.

3. Experimental setups(TS-3 and TS-4)



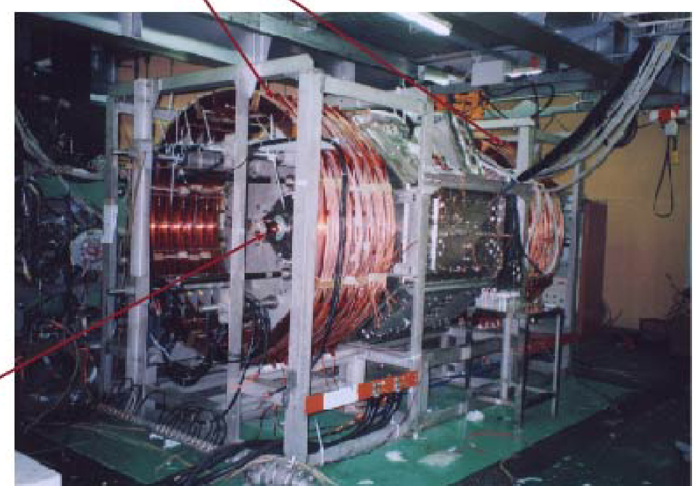
TS-4 machine

Fluxcore



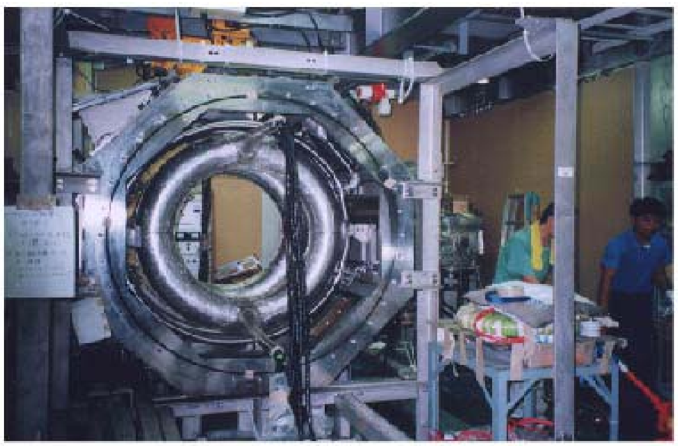
Separation coil(ϕ=700mm)

EF coils

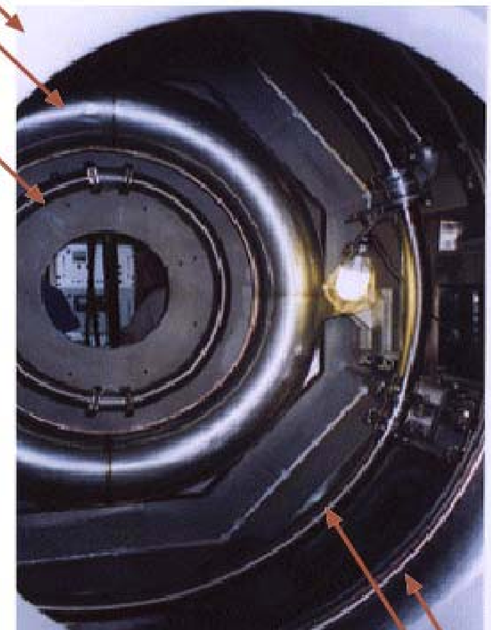


Center Coil

Internal structure of TS-4



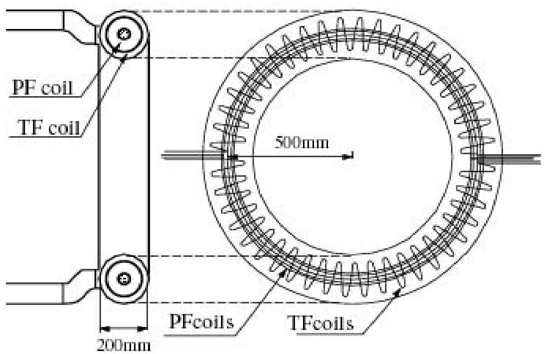
the outside view



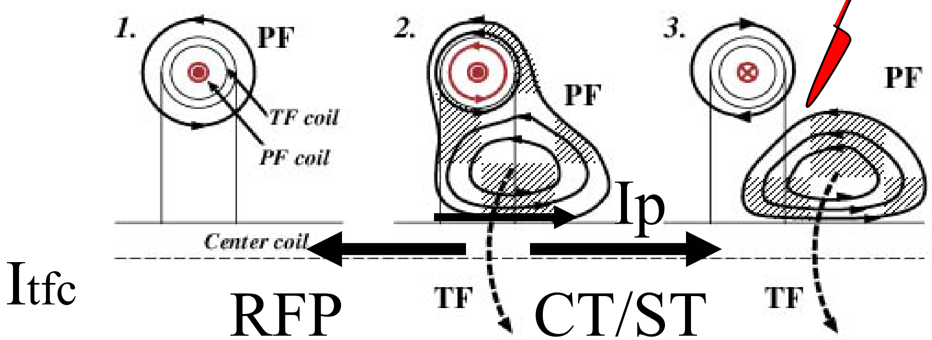
the inside view

Single and double spheromak productions in TS-4 without use of the center OH coil

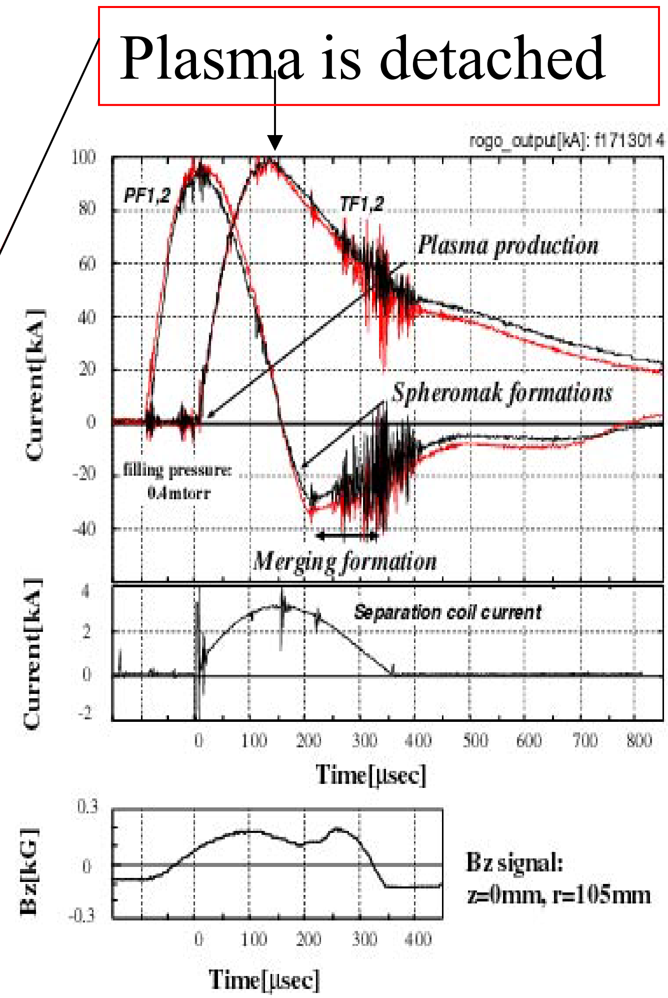
In the following experiments, the same exciting condition is applied.



<Plasma production>
Inductive method by flux core



Inductive method by using fluxcore



To produce a couple of CT/ST's separately in the right side and the left side with the assistance of the center separation coil;

(in TS-3) eight pairs of electrodes and poloidal field coils are located on each side.

(in TS-4) a pair of the flux cores that contains both of the toriodal coils and poloidal coils are located on each side.

The toroidal flux polarities of the two spheromaks can be independently controlled;

(in TS-3) by the directions of the discharge currents between the electrodes, and

(in TS-4) by the polarity of the poloidal flux swings with the toroidal coils in the flux cores.

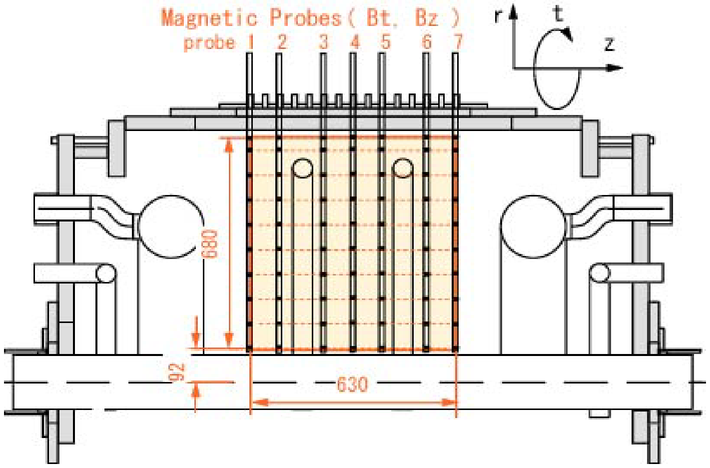
It allows us to conduct both of

the co-helicity merging and the counter-helicity merging

Magnetic probe array

A two-dimensional magnetic probe array composed of about 140 pick-up coils covered with thin glass tubes of 5mm diameter is placed on the R-Z to measure the 2-D profiles of axial and toroidal magnetic fields, Bz and Bt, on a single discharge.

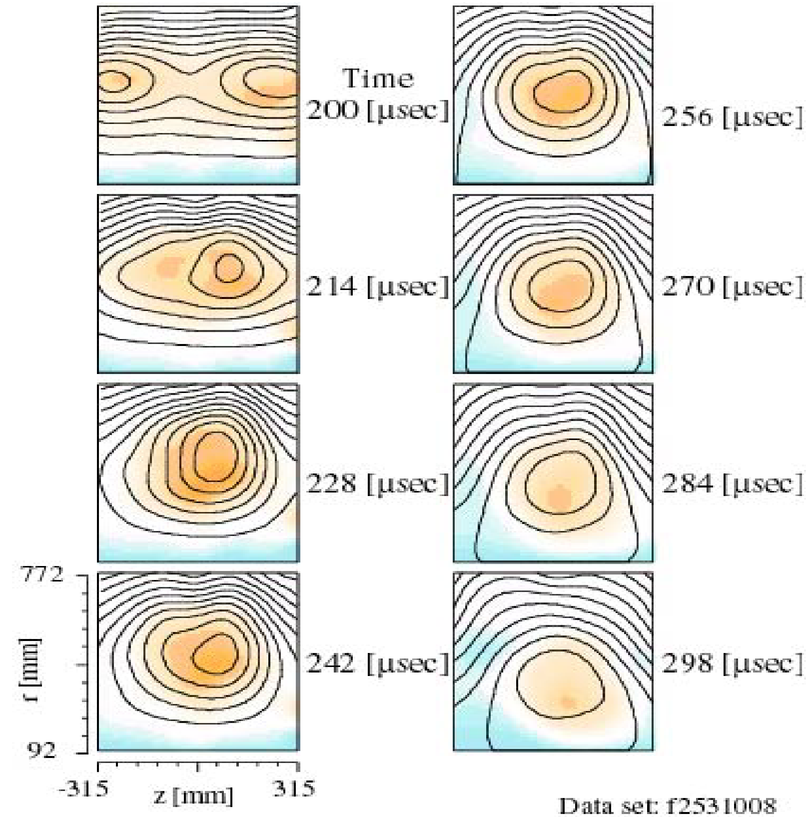
These data are used to calculate the 2-D contours of poloidal flux and toroidal field amplitudes on the assumption of axisymmetric onfiguration.



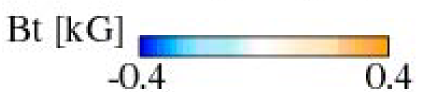
4. Merging produced compact RFP plasmas

- Itfc ~ -8kA produces compact RFPs with A = 1.23 (R~0.5m).
- Co-helicity merging proceeds very fast and the RFP configuration is produced.
- Single RFP production at either side can not be operated because of strong instability.

q_0 = 0.3-0.4 was observed

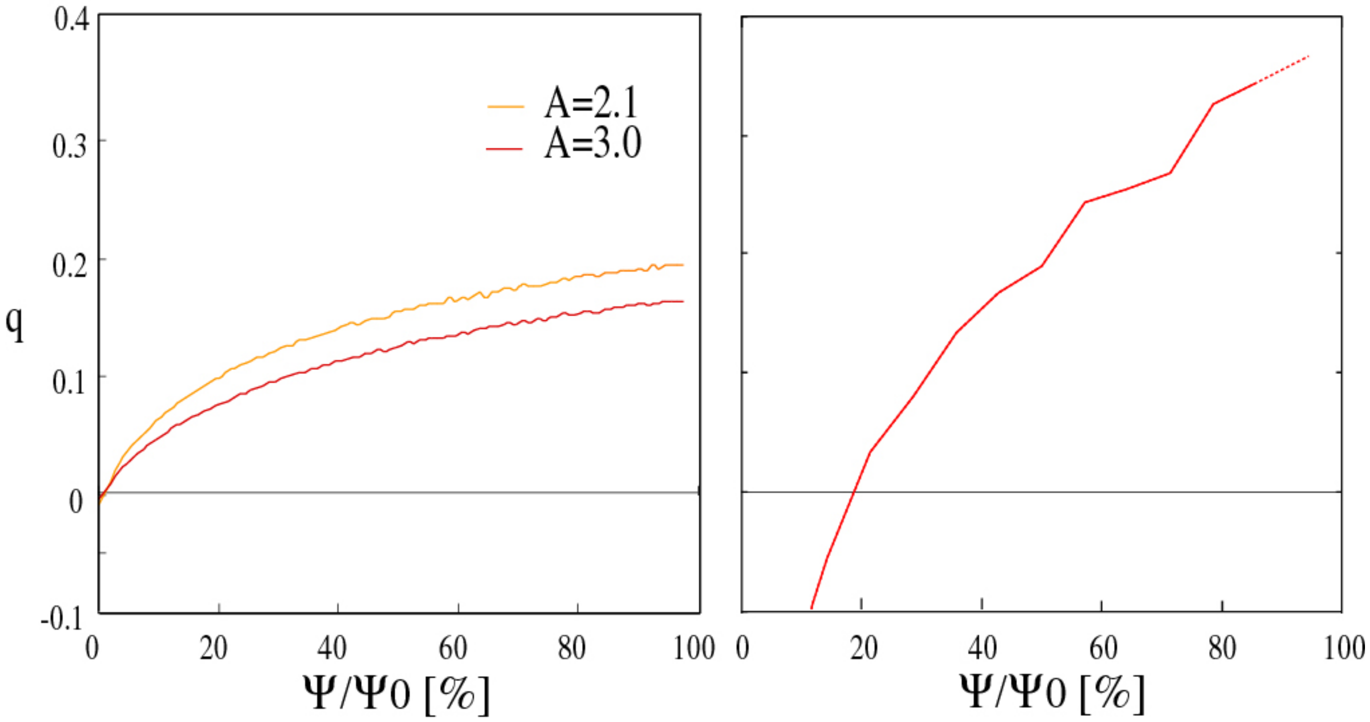


Psi Contour Spacing 2 [mWb]



Poloidal flux contours and toroidal field amplitude.

- The produced RFPs with A=1.23 have higher center-q values than that of conventional RFPs. The number of the rational surfaces was reduced significantly in low-A RFPs particularly in the center region that nay modify the dynamo effect.

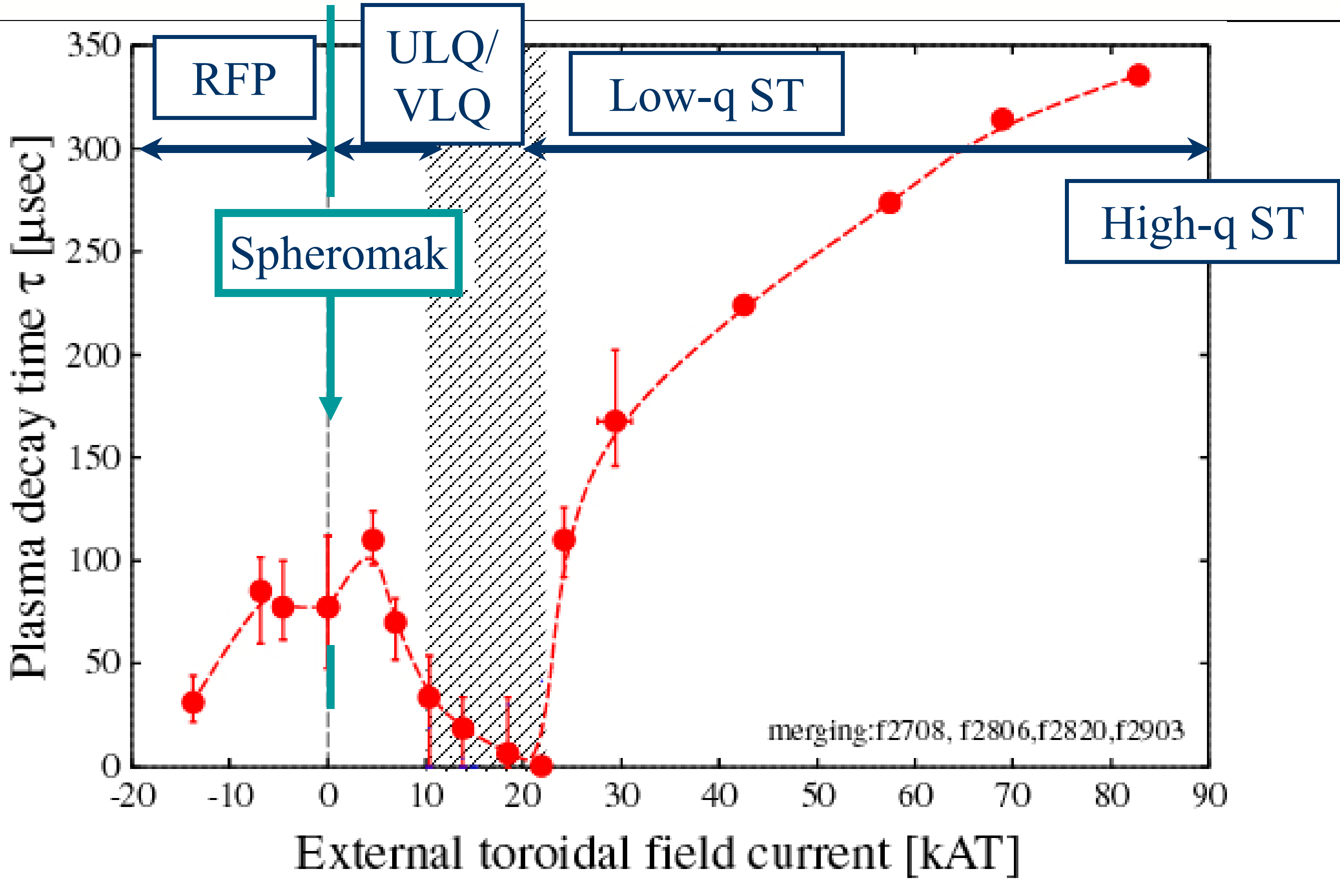


RFPs with A=3.0, 2.1
(Equilibrium calculation)

TS-4 CRFP with A=1.23

Comparison of q-profile with conventional RFPs

1. Using the same method of co-helicity merging, various CT/ST can be made in a various values of the Itfc.
2. Decay time τ of RFP is shorter than those of other configurations.
3. In a large negative external toroidal field, RFP can not be produced.
4. There is a forbidden region in the CT area.



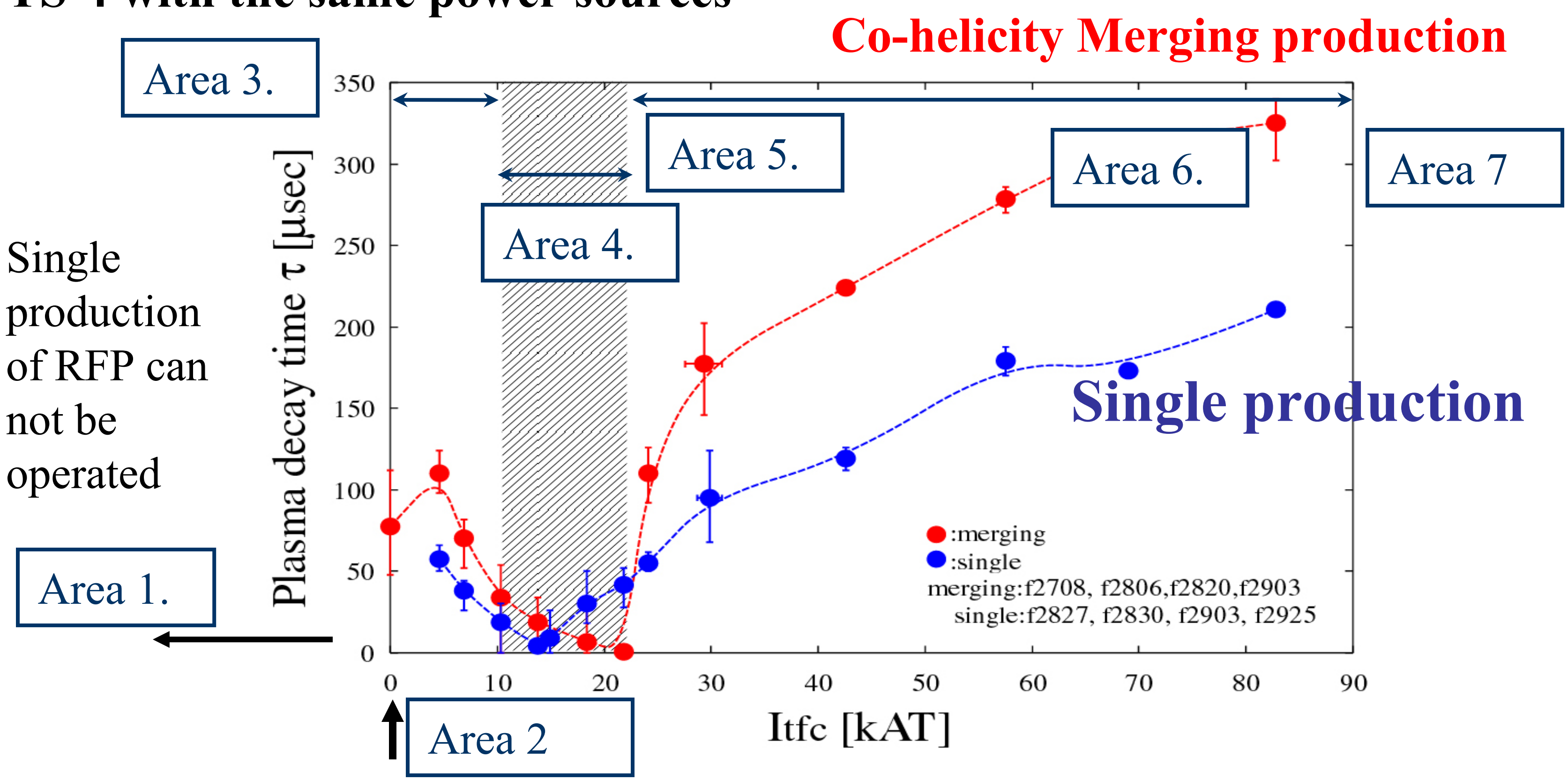
5. Single and Merging productions of CT/ST plasmas in external toroidal fields (except RFP)

Seven operational regimes show different decay times :

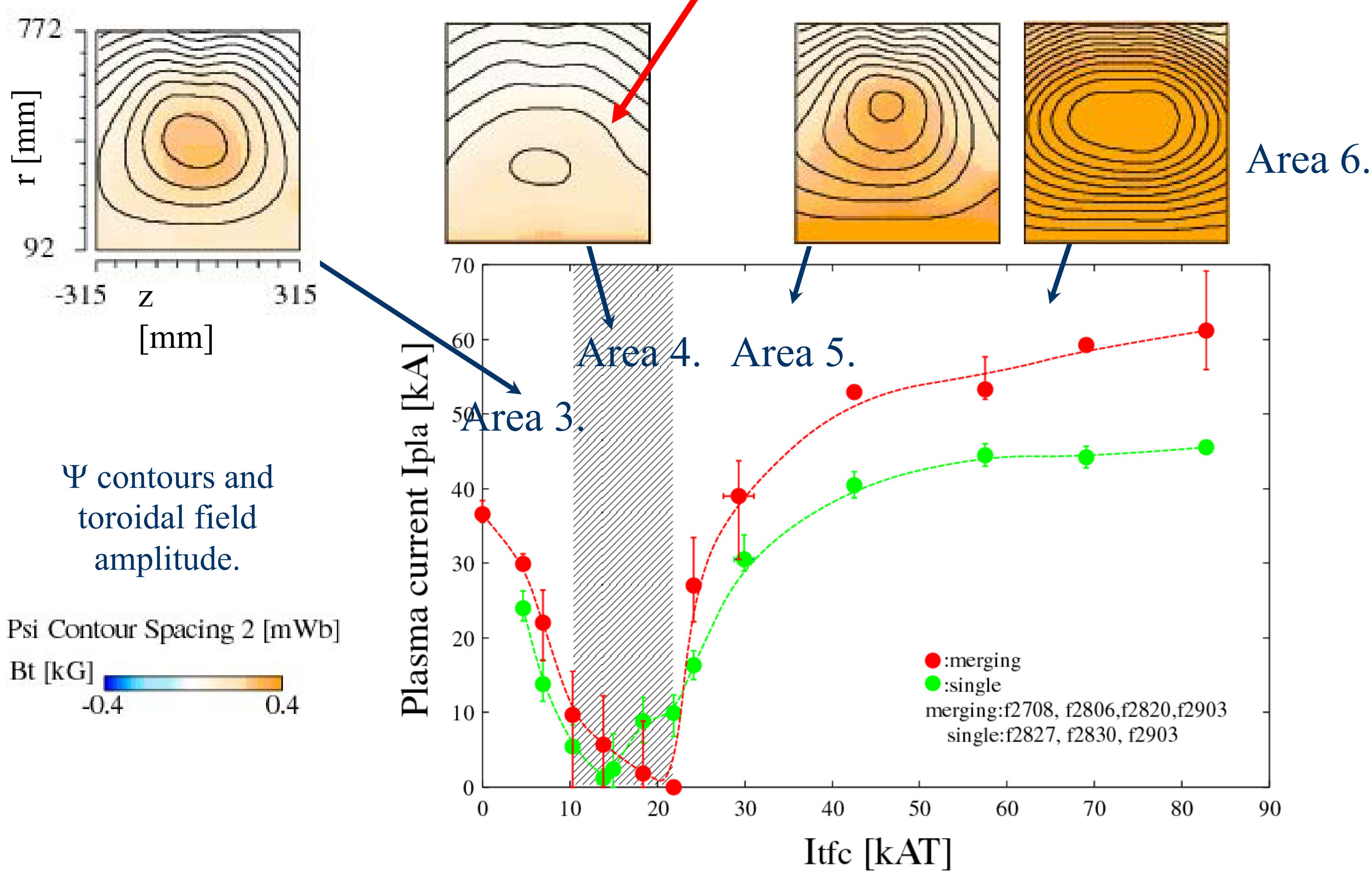
(Area 1: RFP) Area 2: Spheromak Area 3:ULQ/VLQ Area 4: Forbidden

Area 5: Low q ST Area 6 : Middle q ST Area 7: High q ST

TS-4 with the same power sources

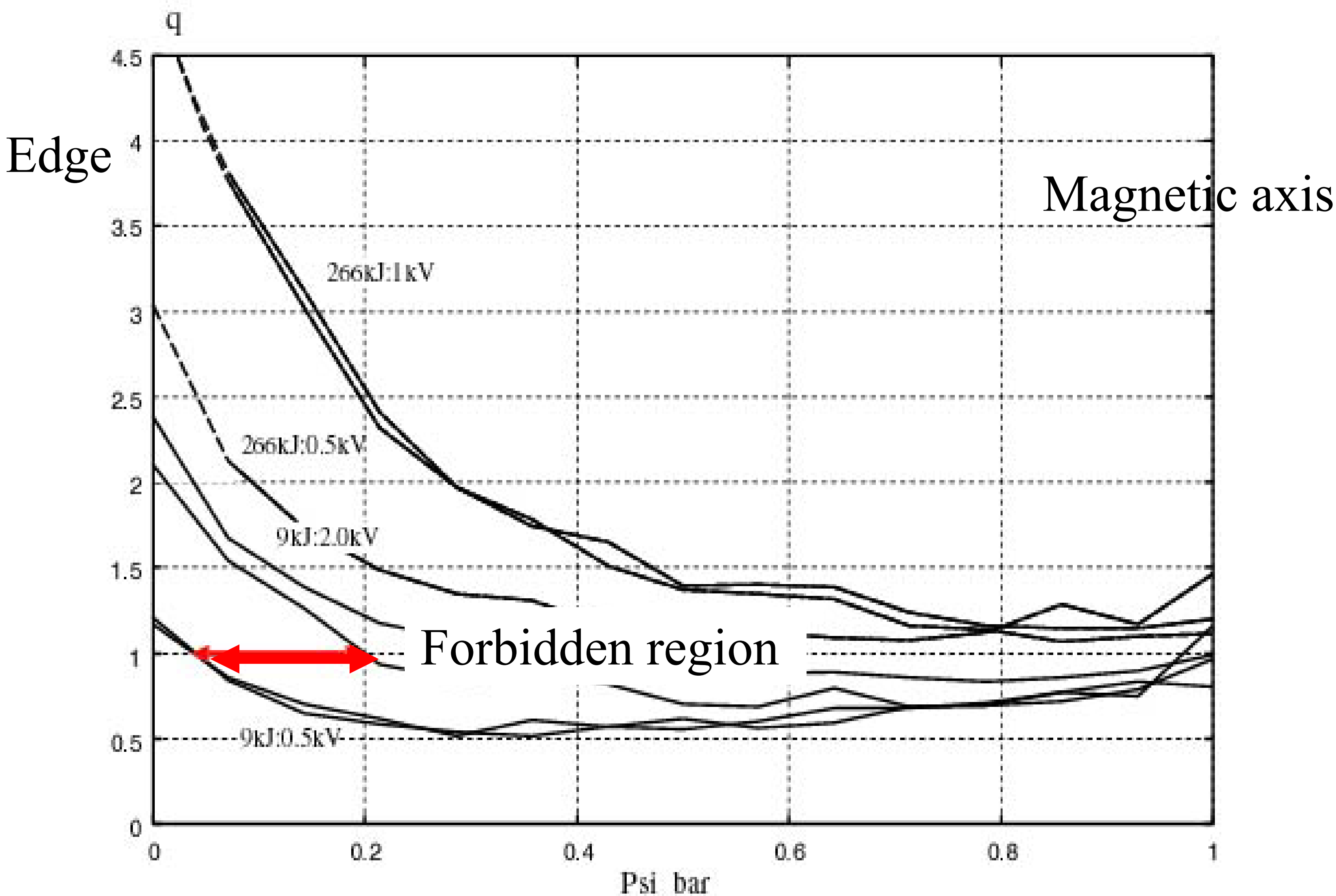


Plasma current vs. Itfc : In area 4, ST is not produced.



Internal q profile of ST's as a function of Itfc

The forbidden region of the Area 4 shows q~1



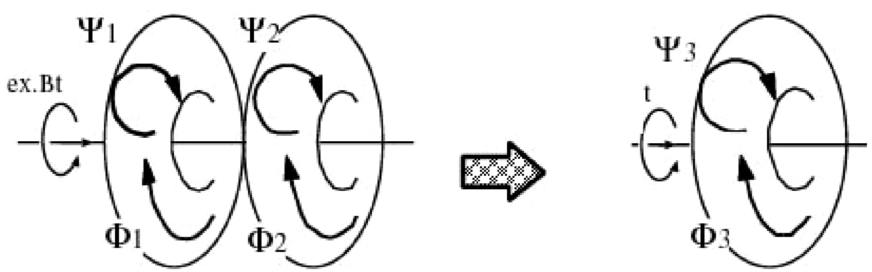
6. Axisymmetric merging and MHD relaxations

The axisymmetric merging injects toroidal fluxes into the region that consists of two domains with originally the same poloidal fluxes.

Internal

Poloidal flux: Ψ_3 same $\Psi_1, \Psi_2)$

Toroidal flux: $\Phi_3 = \Phi_1 + \Phi_2$



$\Psi 3 <= \Psi 1 = \Psi 2$

The poloidal fluxes in the merged CT keep the same original values.

{The toroidal currents should have the same direction}.

Internal q vales on internal poloidal flux surfaces are;

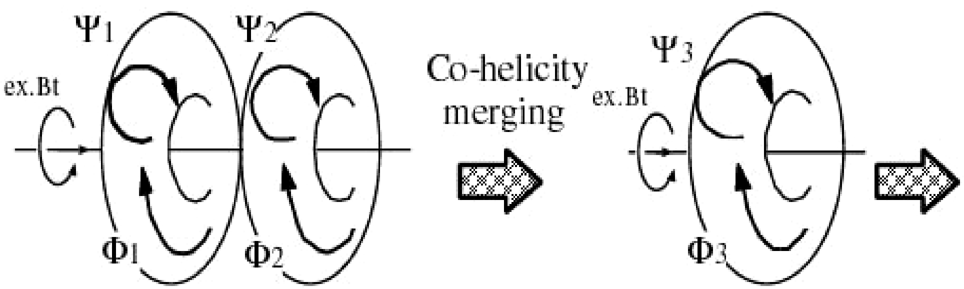
$$q \quad = q1 + q2$$

When the axisymmetric merging proceeds, only toroidal fields are added.

total

Poloidal flux: $\Psi_3 = \max(\Psi_1, \Psi_2)$

Toroidal flux: $\Phi_3 = \Phi_1 + \Phi_2$

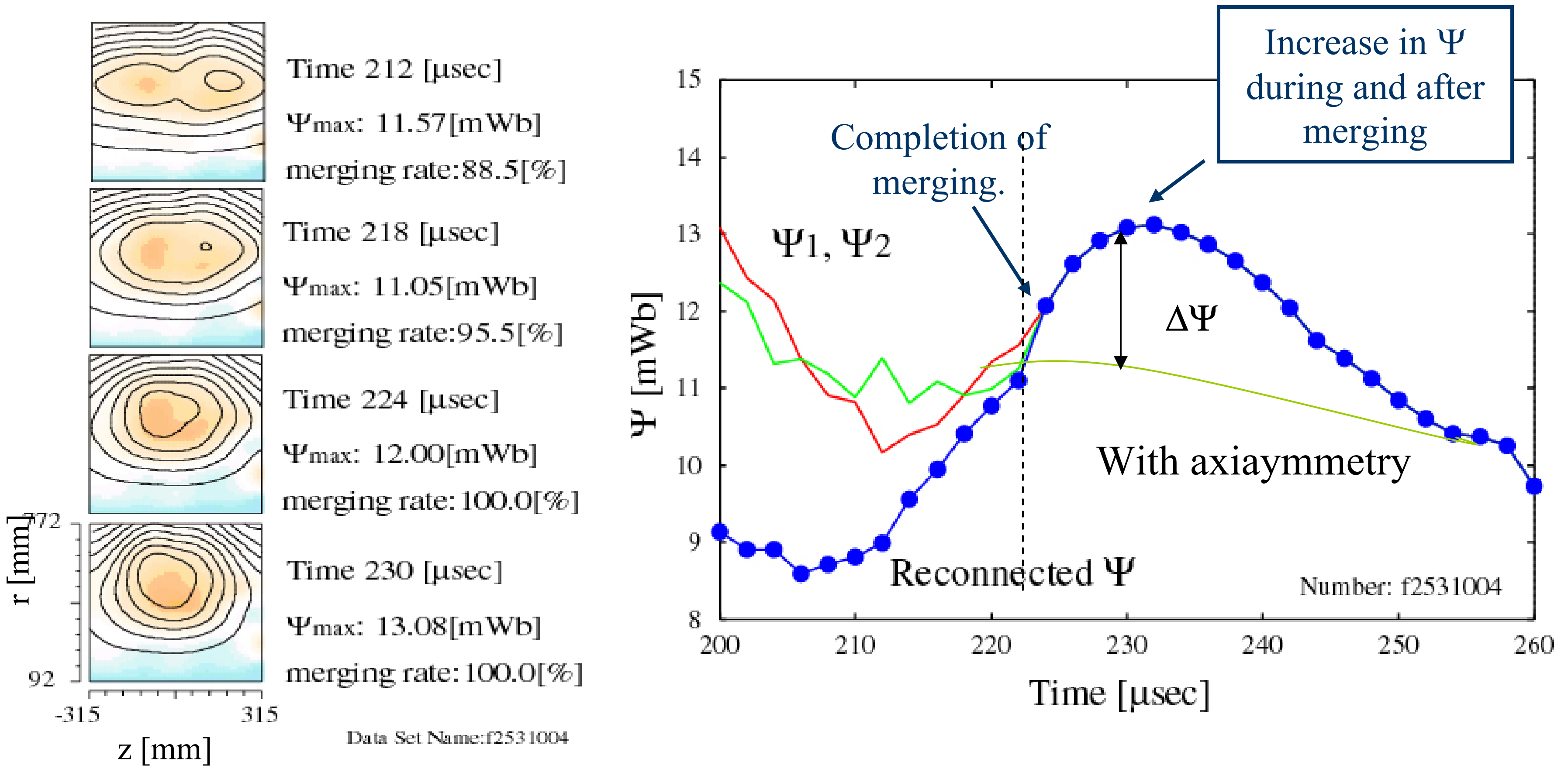


When the merged configuration is MHD unstable, excessive toridal flux is partially converted to poloidal flux to recover the stable Taylor state.

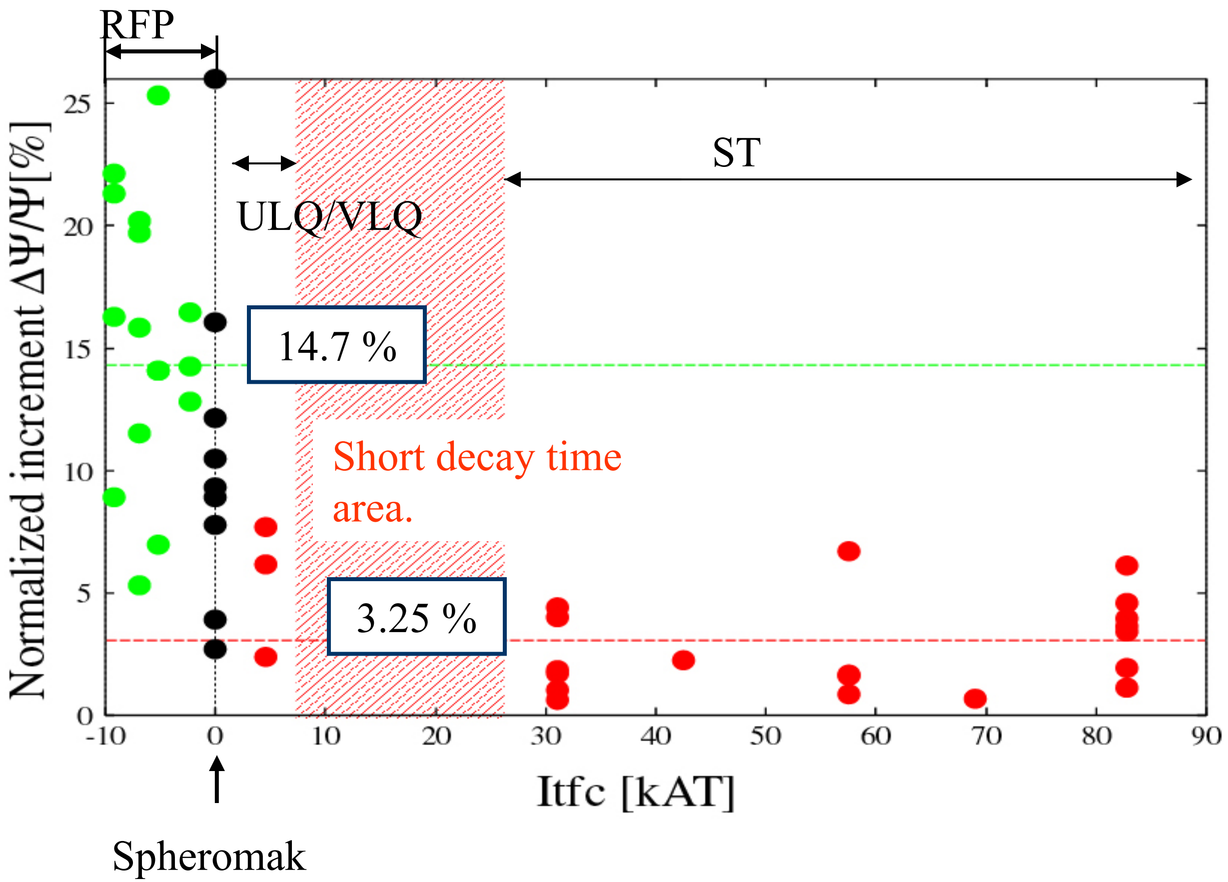
The observation of the magnetic relaxation in co-helicity merging produced plasma is suitable means to evaluate the MHD stability of the configuration.

7. MHD relaxations in low beta CT/ST plasmas

The co-helicity merging produced RFP shows very clearly the increase not only the toroidal flux but also the poloidal flux. The poloidal flux increase after the merging is a very nice demonstration of the MHD dynamo effect.



- **Co-helicity merging productions of RFP and spheromak shows average poloidal flux increments of $\Delta\Psi/\Psi$ = 14.7 [%].**
- **ULQ/VLQ and ST shows average $\Delta\Psi/\Psi$ = 3.25 [%]**



Dependence of ΔΨ/Ψ on Itfc

The n=2 mode is the dominant MHD instability of compact RFP during the flux conversion from toroidal to poloidal.

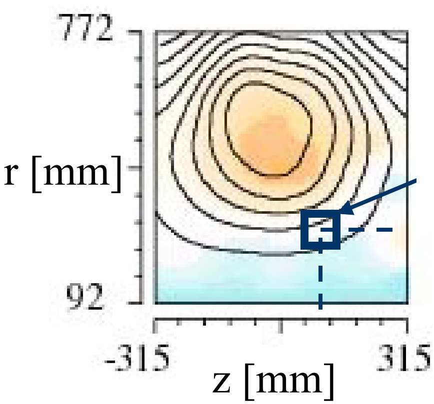
n=0-4 modes for Br, Bz,Bt components.

RED: Bi, n=1 / | Bn=0| i = r, t, z

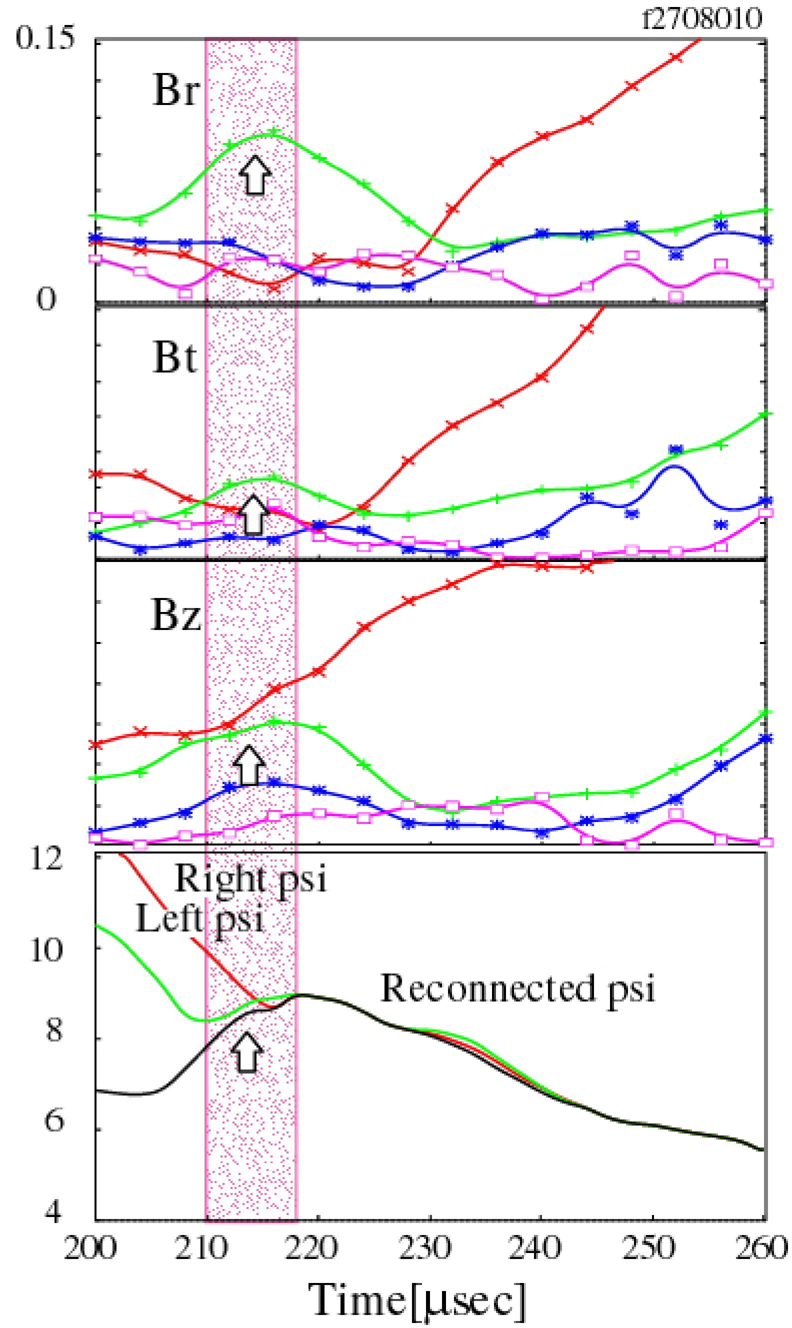
GREEN: Bi, n=2 / | Bn=0| i = r, t, z

BLUE: Bi, n=3 / | Bn=0| i = r, t, z

PINK: Bi, n=4 / | Bn=0| i = r, t, z



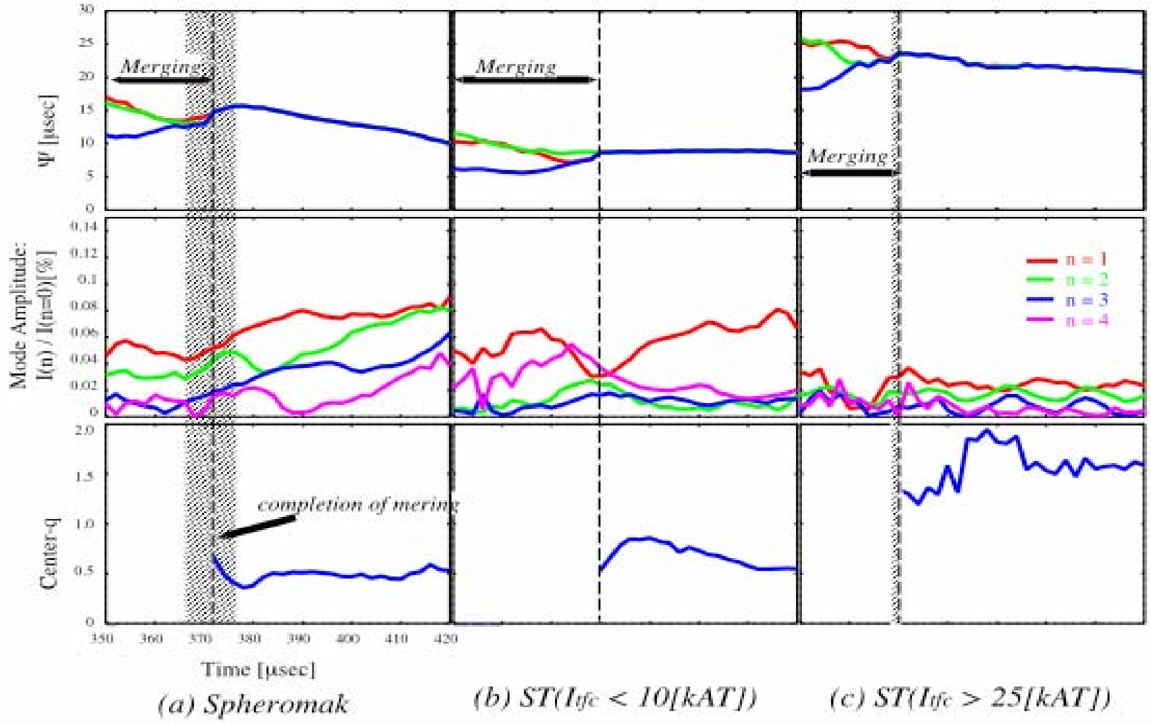
The probe position (r, z)=(294.5, 77)



Toroidal mode measurement

•Clear increases in poloidal flux and n=2 mode were not observed in STs.

• Center-q value of ST increase instead of Ψ after merging.

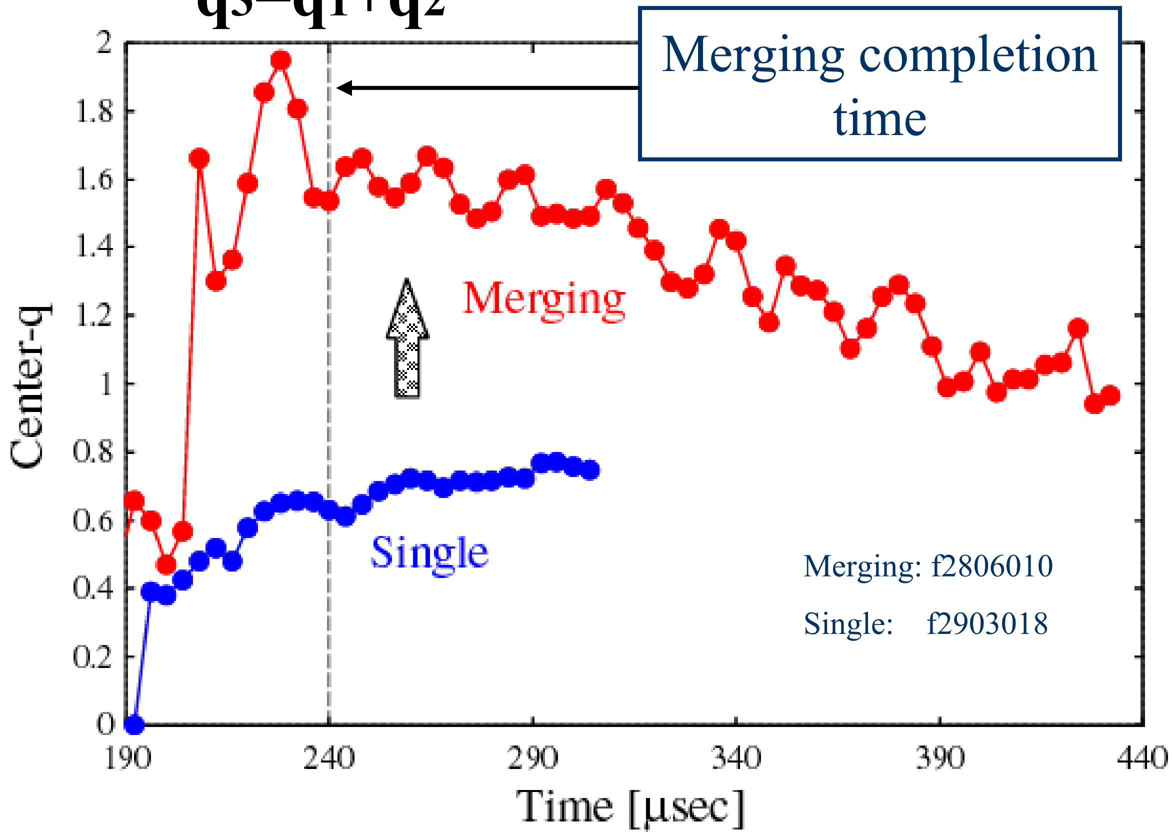


ULQ/VLQ ST (b) with q_0 <1 is as MHD active as RFP and spheromak

Merging formation vs. single formation of STs

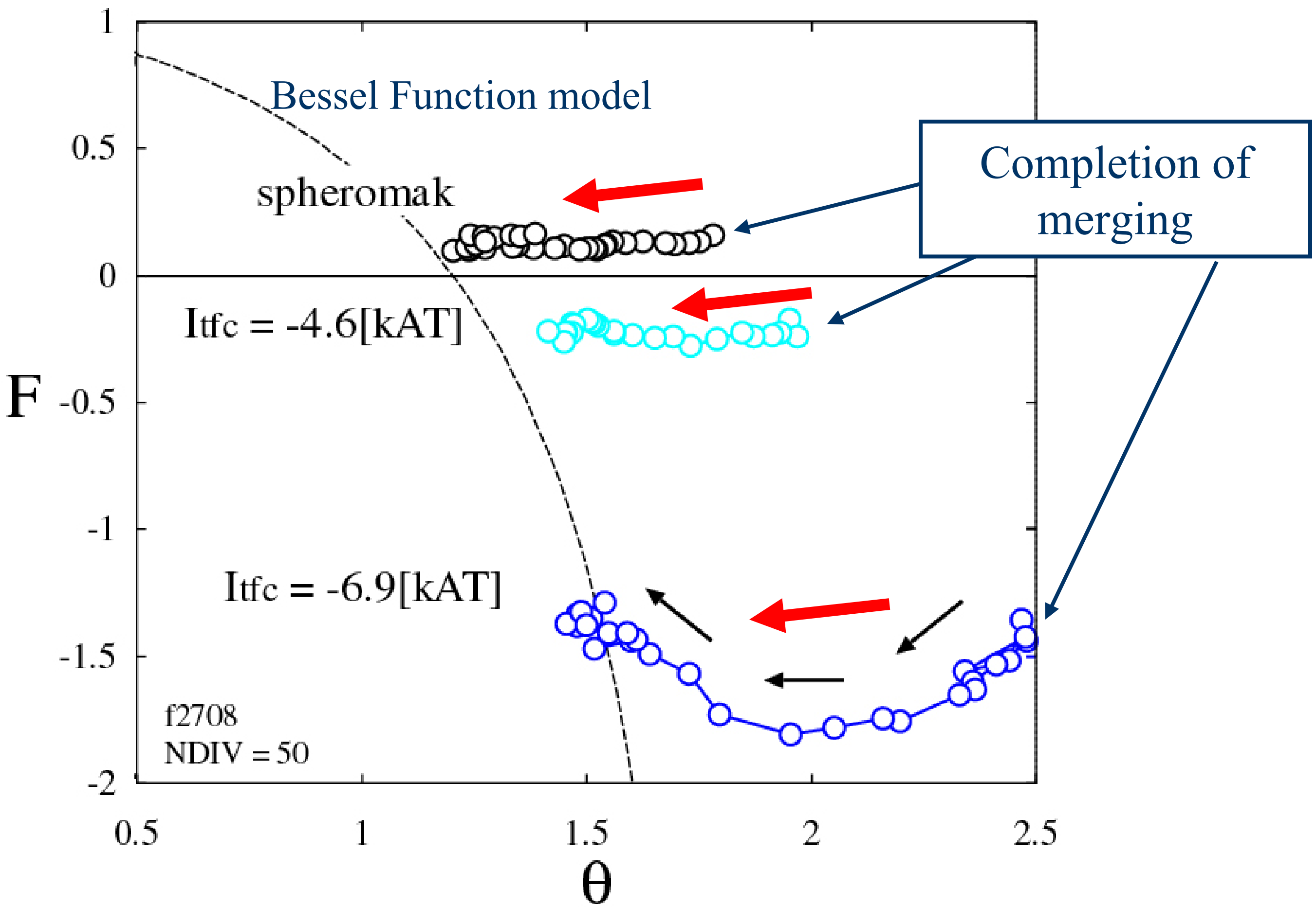
The co-helicity merging of high q ST keeps axisymmetric merging, enhancing toroidal flux in plasmas without relaxation. Therefore, center-q of ST was almost doubled after merging.

$q_3=q_1+q_2$



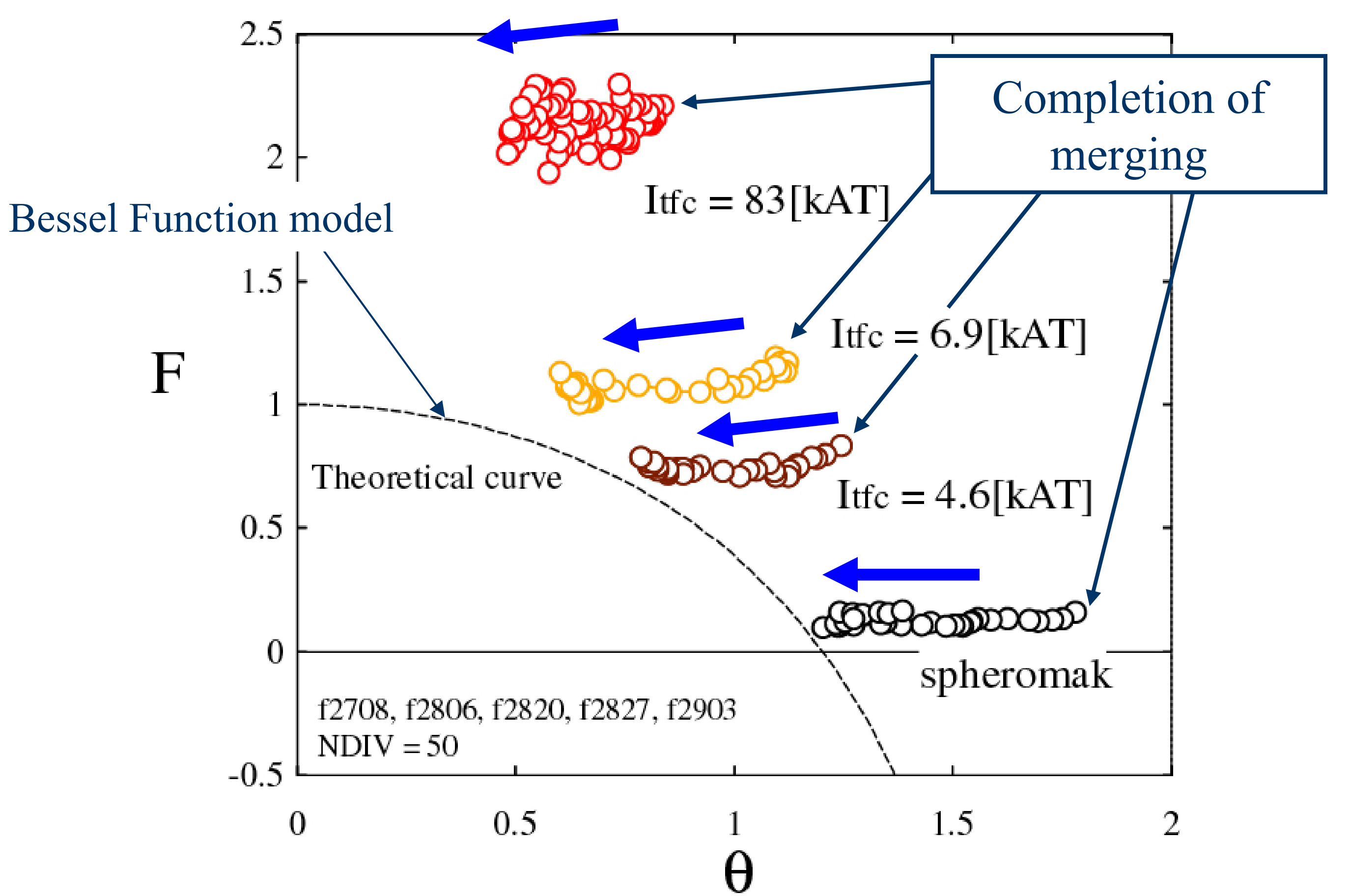
Center-q time evolution of single and merging ST

- RFP had high θ just after the merging.
- It approaches to Taylor state after the relaxation.



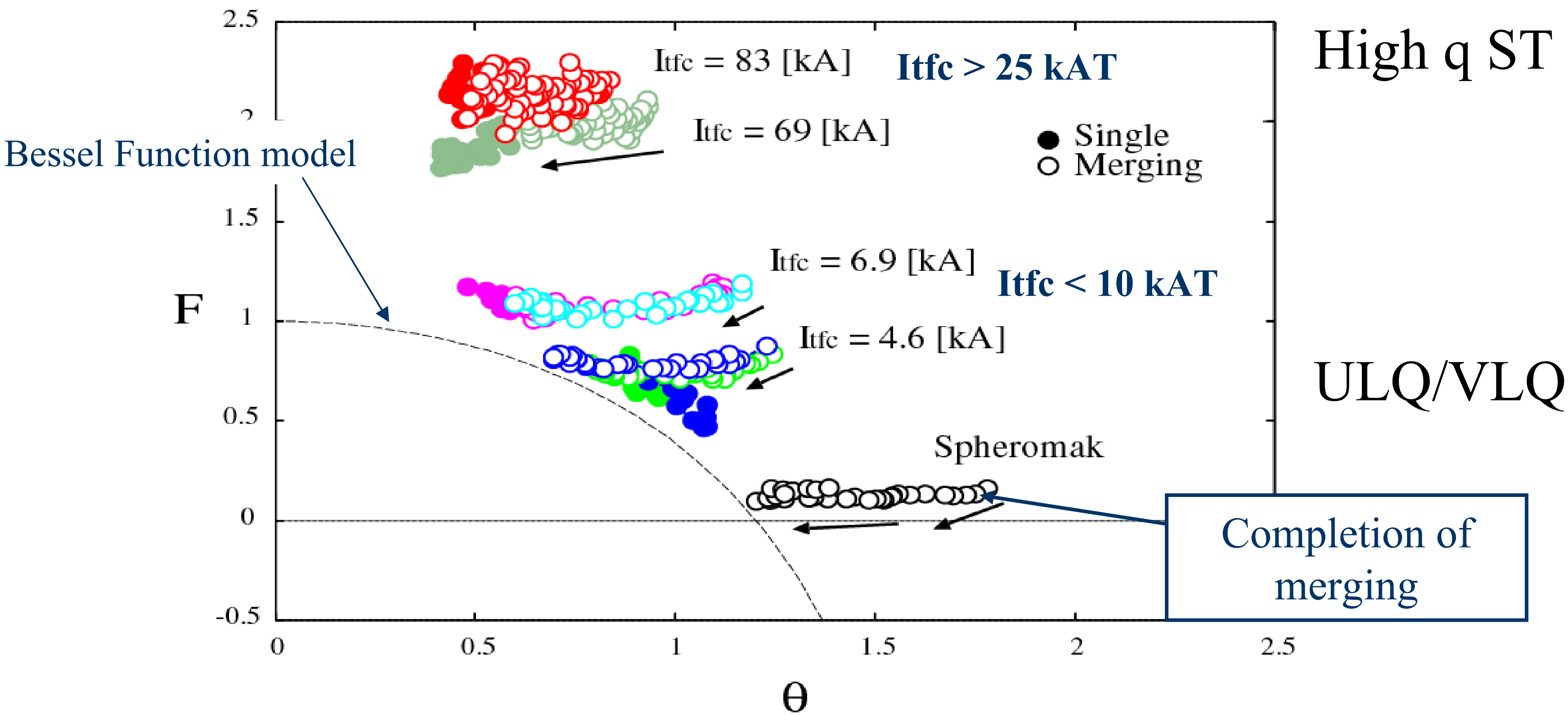
F-θ diagram (compact RFP)

- The F-θ curves of high-q STs(Itfc > 25 [kA]) were deviated from the theoretical curve.
- ULQ/VLQ(Itfc < 10 [kA]) approaches the Taylor state theoretical curve.



F-θ diagram (ULQ/VLQ and ST)

- The merging ST had higher θ than the single ST.
- The merging produced ST relaxed to the single ST state.



F-θ diagram

(merging and single ST and ULQ/VLQ relaxations)

8. Trail to generate high beta ST by counter-helicity merging in external toroidal fields

The counter-helicity merging annihilates their opposing toroidal fluxes. We have used TS-3 machine to demonstrate that the counter-helicity merging of spheromaks generates an FRC with Bt≈0 and beta~1. This merging formation has several advantages over the conventional theta-pinch formation of FRC:

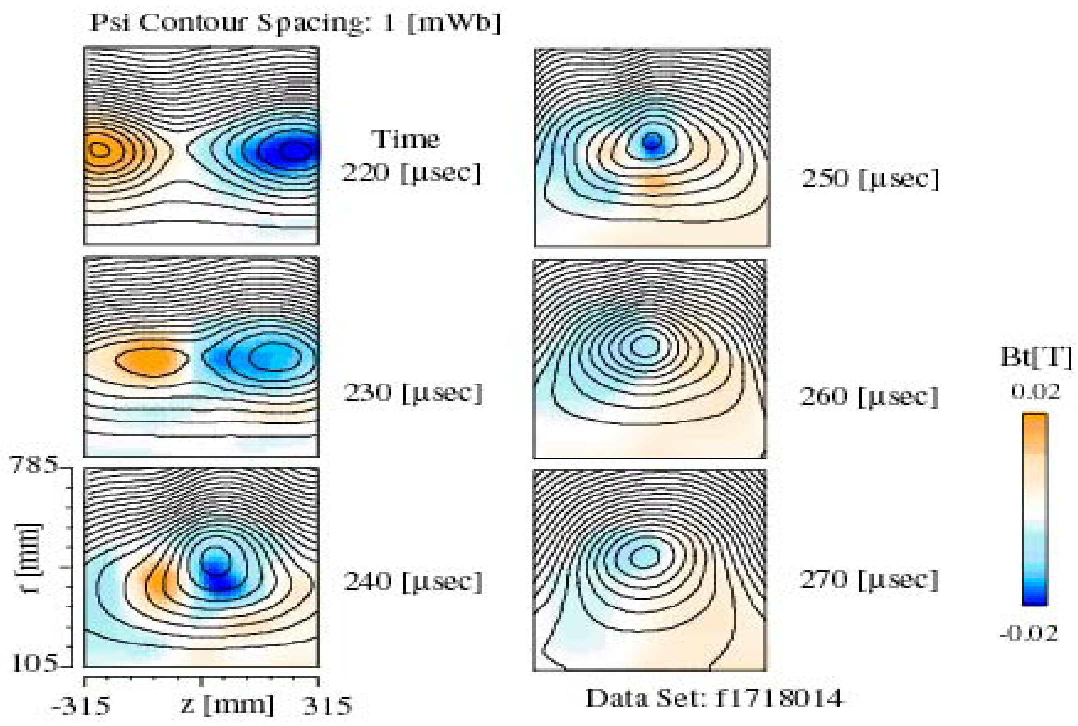
- **(1) High reliability of the formation. Rough similar values of the antiparallel toroidal fluxes brings about the relaxation to FRC with zero toroidal field.**
- **(2) Slow and stable quasi static formation process using minimum energy spheromaks in the Taylor states permitting the elimination of expensive fast capacitor bank,**
- **(3) The fast magnetic reconnection for an efficient rapid ion heating within the energy confinement time, and**
- **(4) Internal heating free from impurity contaminations.**

Experimental results with TS-4 machine

FRC production by the counter helicity merging.

We successfully confirmed the production of FRC by proper controls of the separation coil currents.

Operations with a lower filling pressure result in the productions of FRC's with a properly lower electron density.



Trials to produce high-beta ST in TS-4

The TS-4 machine has larger toroidal field coils with a larger inductance compared to the TS-3 machine, it is not easy to rapidly post-inject the external toroidal field into the FRC to form high-ß ST's as has been carried out with the TS-3 machine.

We have been investigating the pre-injection method:

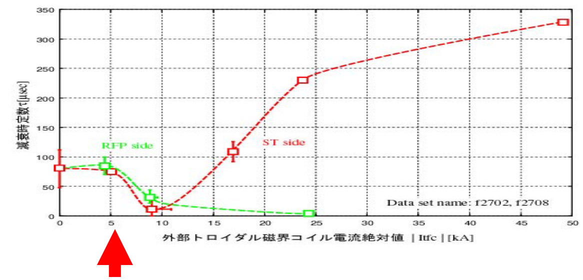
1. In advance, an external toroidal field is quasi-statically supplied by the center current .

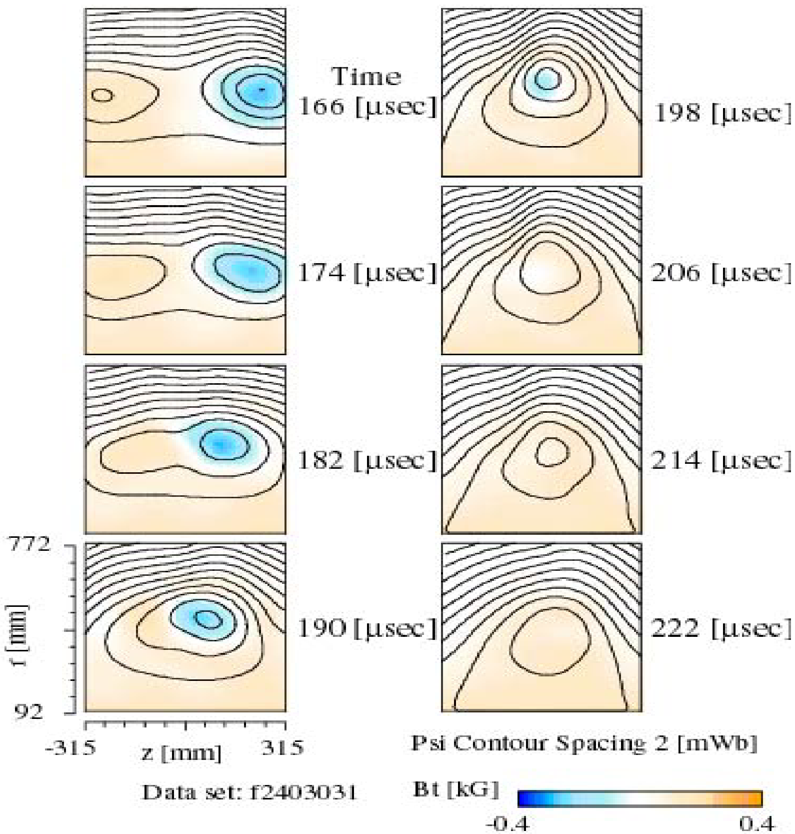
2. The couter helicity CT's are separately produced <u>in the external toroidal field.</u>

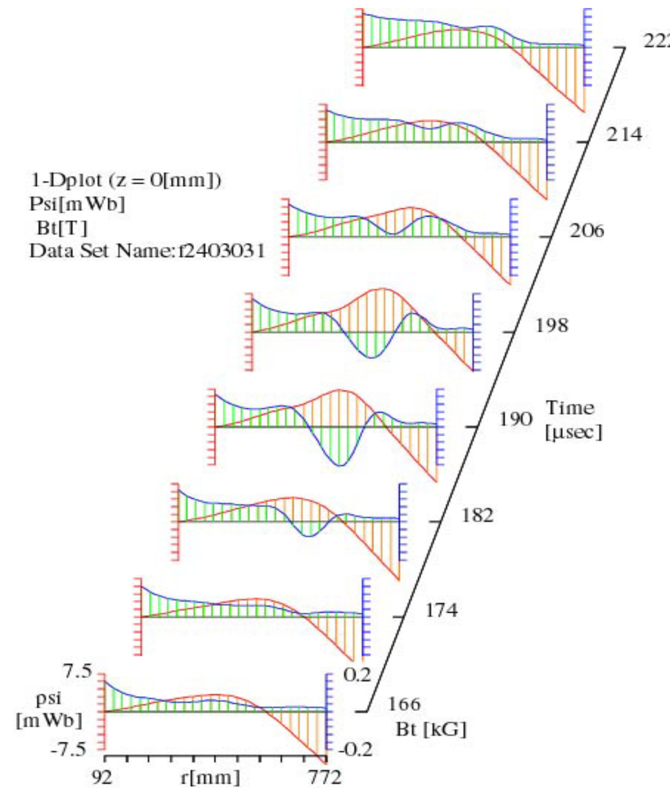
In this case, two counter helicity CT`s produced in the same external toroidal field are <u>ST and RFP</u> (Reversed Field Pinch), respectively.

Only low Itf operation

(ULQ/VLQ regime) can be studied







Production of ultra high beta ULQ/VLQ

- **In this operation, the magnetic fields and plasma currents are very week, about 0.02T and about 50kA, respectively, indicating the operations with q-edge less than 1, (what are called ULQ/VLQ regime) .**

- **Even after the merging is completed, the polidal flux of the RFP-side survives and the opposing RFP-type toroidal fields coexist in single plasma,**

- **The experiments are still in preliminary phase.**

- **The utra high-beta ST with the magnetic well(hole) is theoretically suggested by: M.Warrier, R.Srinivasan, P.K.Kaw, Physics of Plasmas, 9(2002) pp3075~3081.**

Trials to produce high beta ST with q>1 are still under investigation.

The lifetime increase of RFP side is necessary.

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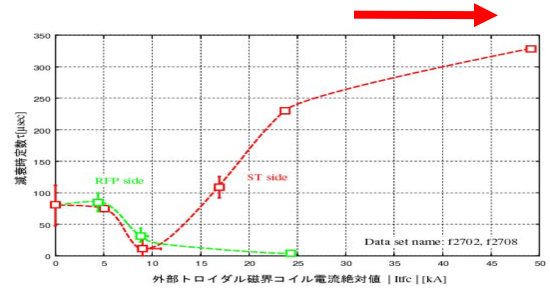
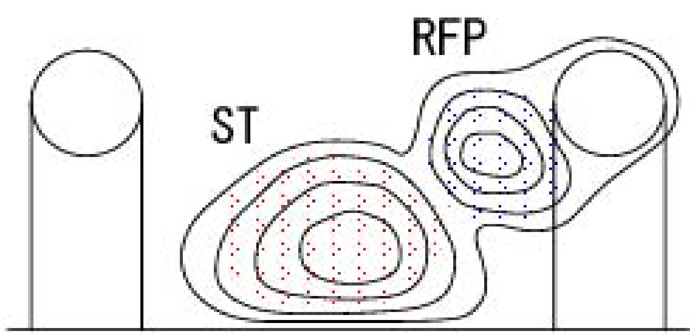
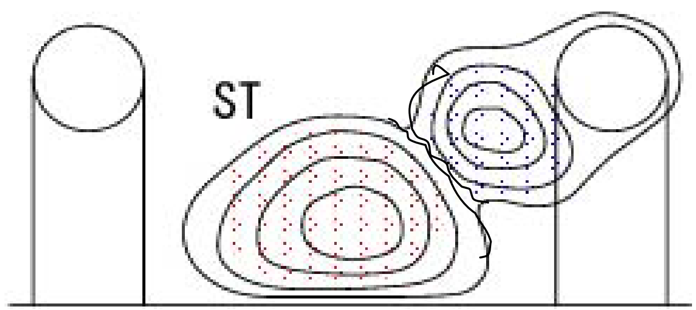




Flipped counter-helicity ST ?



9. Concluding remarks

- ***A comparative study of all class of CTs and STs: compact RFPs, spheromaks, ULQ/VLQ, and STs, was made in varied external toroidal field current I_{tfc} (I_{tfc} =-15~80[kAT]) in TS-4 device.***
  - The range of $I_{tfc} < 0$ where the RFP can be produced is very narrow.
  - The range 10kA< I_{tfc} <20kA is the forbidden range where the abrupt decrease in decay time was found. q-value of the produced ST was around 1.

- ***Relaxation in RFP and spheromak regime***
  - Increase in poloidal flux was observed together with n=2 mode after co-helicity merging. Taylor relaxation and strong MHD activity is observed.
- ***Relaxation in ULQ/VLQ regime***
  - Enough information is not yet available.
  - Taylor type relaxation but no increase in the poloidal flux.
- ***Relaxation in ST regime***
  - No Taylor relaxation / flux conversion was observed not only in single ST but also co-helicity merging produced ST
  - q-value scan from spheromaks through low-q STs to high-q STs revealed gradual increase in plasma decay time τ that is very long compared with those of CT etc..

- ***The high beta ST formations by the counter-helicity merging needs further investigation.***
  - The pre-injection of week Bt (the counter helicity merging of a ULQ/VLQ and an RFP in the same *week* external toroidal field) can produce a high-ß ULQ/VLQ .
  - The pre-injection of a stronger external Bt needs further investigations to demonstrate the formation of a ultra high-beta ST with an ordinary q-edge value (q_{edge}) more than about 5.
- ***Optimaized configuration would be found through this study.***